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802.16e System Profile for NASA Extra-Vehicular Activities

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Abstract - **This report identifies an 802.16e system profile that is applicable to a lunar surface wireless network, and specifically for meeting extra-vehicular activity (EVA) data flow requirements. EVA suit communication needs are addressed. Design-driving operational scenarios are considered. These scenarios are then used to identify a configuration of the 802.16e system (system profile) that meets EVA requirements, but also aim to make the radio realizable within EVA constraints. Limitations of this system configuration are highlighted. An overview and development status is presented by Toyon Research Corporation concerning the development of an 802.16e compatible modem under NASA's Small Business Innovative Research (SBIR) Program. This modem is based on the recommended system profile developed as part of this report. Last, a path forward is outlined that presents an evolvable solution for the EVA radio system and lunar surface radio networks. This solution is based on a custom link layer, and 802.16e compliant physical layer compliant to the identified system profile, and a later progression to a fully interoperable 802.16e system.**

I. INTRODUCTION

In 2004, the Bush administration unveiled the United State's Vision for Space Exploration (VSE) [1]. This included the very ambitious goal of creating and sustaining a human presence on the Moon and Mars. NASA's plan for achieving the VSE was first introduced in the Exploration Systems Architecture Study (ESAS) released in November of 2005 [2]. Since this time, NASA has embarked upon a number of agency-wide, inter-center studies to further develop and refine the exploration architecture as presented in the ESAS final report.

NASA's Lunar Architecture Team produced a report that identifies the 802.16e standard as the wireless technology of choice for lunar surface-to-surface radio communications [3]. The study identifies the architecture and required data capacities of a surface 802.16e system without defining a specific configuration or "system profile", as appropriate for an architecture study.

Under Constellation Systems, the EVA Exploration Technology Development Program (EVA ETDP) has initiated an effort to evaluate configurations of this 802.16e standard, as well as identify the capabilities it lacks and the innovations that will be required by NASA.

II. OBJECTIVES

There are three objectives for this study. First, a high level system profile must be identified that supports the requirements for the EVA system. "System profile", with regards to the IEEE 802.16 standard and amendments, refers to a particular configuration of the parameters within the standard that form a unique instantiation of a system targeted for a particular market. This allows chip manufactures and system integrators to develop and build 802.16 systems that are interoperable for specific deployments. A system profile, at a very high level, defines these characteristics:

- radio network topology
- duplex scheme
- power class
- radio frequency
- signal bandwidth

- slot time

The second objective is to evaluate the feasibility of developing a modem based on the identified system profile that will have a path to space flight, as well as minimize size, weight, and power requirements.

The last objective is to identify or develop a scheme in which point-to-point communications between EVA astronauts can be accommodated. The 802.16 standard describes a mesh mode of operation; however this is an optional mode of operation and has not been implemented in commercial equipment. It is highly desirable, although not required, to utilize as many common hardware/firmware/software components for both modes of operation as possible.

III. 802.16e SYSTEM PROFILE IDENTIFICATION METHOD

The following is an outline of the method used to satisfy the first objective of this study:

1. Identify the EVA system communications requirements.
2. Identify and characterize the data flows involved with EVA operations.
3. Create a subset of communication operational scenarios that define how these requirements are realized.
4. Determine the data capacity of all configurations (system profiles) of an 802.16e system via simulation.
5. Identify an 802.16e system profile that meets the referenced or assumed EVA system requirements, if one exists.

IV. EVA COMMUNICATION NEEDS

Communication requirements for EVA lunar surface operations are not baselined and require further maturation. However, from a functional perspective there are several needs that are envisioned based on draft operational concepts such as:

- Direct suit-to-suit (point-to-point) communications between two crew radios without reliance on external assets.
- Communications between two teams of two crew members through a relay.
- Communications with other Constellation assets such as a habitat, lander, a rover, or a lunar network infrastructure (up to 4 assets during sortie missions, and up to 6 assets during outpost missions).
- Video for situational awareness.
- High resolution video and imagery for engineering and scientific analysis.

These needs are summarized in Table 1. These requirements form the basis for data flow analysis and operational scenario development.

TABLE 1 - EVA SUMMARY COMMUNCATION NEEDS

EVA Communication Needs
Communicate with 4 elements during sortie missions.
Communicate with 6 elements during Lunar Outpost mission.
Provide real-time, standard definition video.
Process telemetry from other systems.
Provide capability to transmit HDTV
Direct suit-to-suit intercom system

Table 1 summarizes both draft and baseline requirements appertaining to EVA communications. These requirements form the basis for data flow analysis and operational scenario development.

V. EVA DATA FLOWS

For the purposes of this study, some basic assumptions are made to estimate the data capacity requirements of a potential 802.16e system profile for EVA.

First, all information is conveyed via UDP/IPv6 packets and incur the corresponding overhead. IP header compression is not assumed. It has also been assumed that this information is optimally packed into the UDP datagrams to the extent that it may be without interfering with the data production rate. As a consequence, voice suffers the highest overhead/data ratio.

Second, for this study constant information generation rates are assumed for all data flows. This is generally applicable for peak traffic loading estimation, but is generally not the method utilized for characterizing traffic loads in packet-based, statistically multiplexed networks. However, a statistical traffic analysis has not been performed for all data flows. Therefore, stochastic models of each data flow do not yet exist. The results of this report, in effect, apply to worst-case traffic loading situation.

TABLE 2 - DATA FLOW SUMMARY

Data Flow	Data Rate
BioMed and Suit Data	2.3 kbps
Nominal Voice (G.729)	61.6 kbps
Standard Definition Video (NTSC Quality)	1.390 Mbps
High Definition Video (HDTV: 720p/ 60 Hz, 120:1 compression ratio)	7.411 Mbps

Table 2 displays the data rates developed in this study, including overhead, for the data flows of interest. This will be used, together with the operational scenarios, to estimate peak aggregate traffic data rate requirements.

Note that a Caution and Warning (C&W) data flow is not included in Table 2. Although the C&W data flow is of high priority, it has a very low data rate requirement and may not be implemented as a network traffic data flow (IP-based). For these reasons, it will have little effect on the peak aggregate data rate requirements.

VI. OPERATIONAL SCENARIOS AND DESIGN DRIVERS

It is necessary to first identify the data flow requirements in order to identify an applicable 802.16e profile as a solution for the radio network on the lunar surface.

A more comprehensive report in this area can be found in the ETDP-EVA-PCAI-0011 - EVA/ETDP 802.16e Lunar System Profile Report [4], in which a number of scenarios are presented that help to identify the aggregated data needs of EVA operations.

Two important assumptions need to be noted regarding this analysis. First, the HDTV “Draft” requirement is not a design driver for this exercise. However, it will be shown that an HDTV data flow can be supported given the 802.16e profile selected.

Second, and most importantly, the optional mesh capability described by the 802.16e standard is not considered a viable option for this application. No current commercial implementations of the optional mesh portions of the standard have been identified. Furthermore, the active 802.16j Relay Task Group [5] is working on the completion of a final draft amendment to the current standard which adds relay capability in the form of small, deployable repeaters. However, in this architecture a base station remains a single coordinator of all radio resources, and the repeaters are deployed to extend the range of the base station’s cell. Therefore, only the Point-to-Multipoint (PMP), cellular 802.16e architectures are considered.

In the 802.16e network architecture for the lunar surface, the base station (e.g Altair, Rover, and/or Habitat) would be the router and arbitrator of all data and radio resources, similar to cellular phone networks. Figure 1 illustrates the possible simultaneous data flows that would need to be supported based on the most data intensive scenario identified in [4] for a PMP architecture, in which the lunar Habitat provides an 802.16e base station.

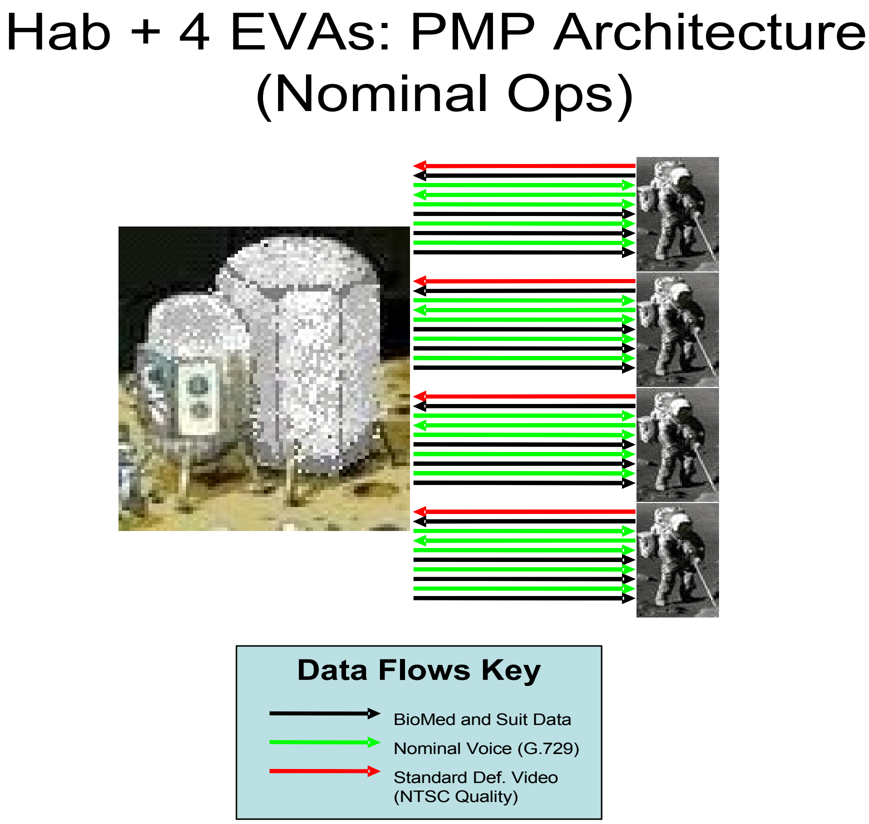

FIGURE 1 - DESIGN DRIVING SCENARIO

This configuration makes the assumption that all voice data flows are simultaneously active at any one time. It is not unrealistic for biomed, telemetry, and operational video to be active simultaneously. These data flows are the major design drivers for the radio network due to their bandwidth consumption.

802.16e also allows for the use of multicast data flows within the architecture. Therefore, individual EVA suits may multicast their biomed, suit telemetry, voice, and operational video to other suits without the need to set up individual connections to each other.

Although the scenario depicted in Figure 1 may not be a typical scenario, the lunar surface radio network needs to provide enough capacity to support these data demands. It is important to note, again, that the EVA astronauts must route all information through the base station (Habitat, Rover, or Lunar Communications Terminal (LCT)) in an 802.16e PMP system.

The aggregate data flow that this system profile would need to support is presented in Table 3.

TABLE 3 – AGGREGATE DATA NEEDS FOR DESIGN DRIVING SCENARIO

Flows	Count	Total (Mbps)
BioMed and Suit Telemetry	16	0.037
Nominal Voice	20	1.232
Standard Definition Video	4	5.560

TOTAL: 6.829 Mbps

The 802.16e high level system profile is selected to support these data flow needs. However, nominal operations with only 2 EVAs will only need to support the data flows identified in Figure 2.

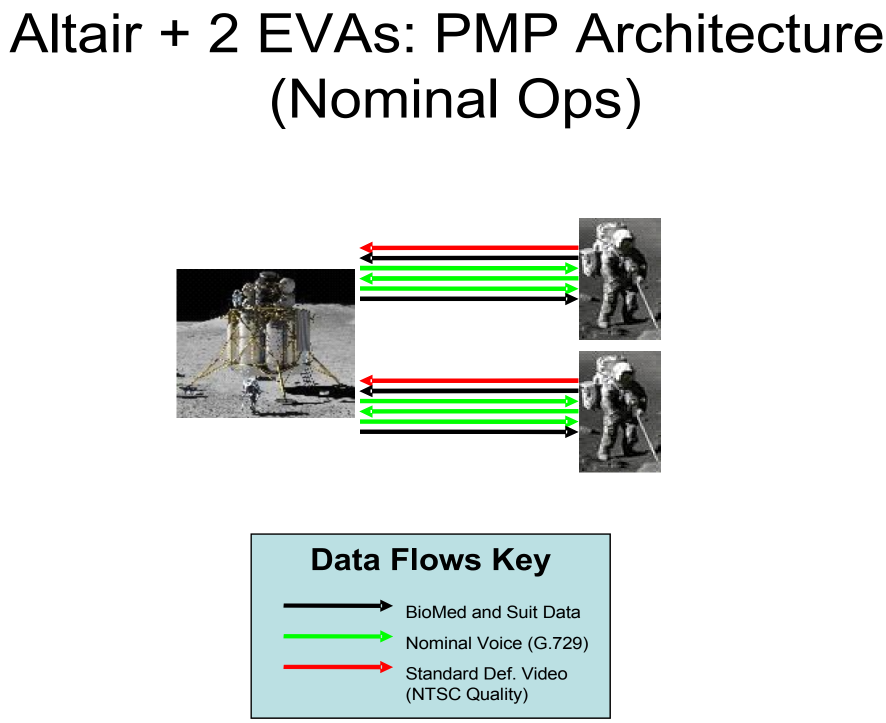

FIGURE 2 - TYPICAL EVA SCENARIO

The aggregate capacity of this scenario is presented in Table 4.

TABLE 4 – AGGREGATE DATA FLOW NEEDS FOR TYPICAL SCENARIO

Flows	Count	Total (Mbps)
BioMed and Suit Telemetry	8	0.018
Nominal Voice	10	0.616
Standard Definition Video	2	2.780

TOTAL: 3.414 MBPS

In selecting an appropriate 802.16e system profile every effort is made to reduce the complexity of both the EVA RF front end and baseband implementation. This will ultimately lead to reduced size, weight, and power values for the EVA radio.

VII. 802.16e SYSTEM PROFILE FOR EVA

The recommendation of this study is to adopt the 802.16e PMP architecture for the lunar surface and potential EVA communications when adequate infrastructure has been deployed. The PMP operations would be ideal for nominal operations in that it is a full reservation-based system (supporting multiple QoS levels), as well as providing power and timing control of the in network radios.

Section XIII of this report introduces an intermediate step toward full PMP deployment of an 802.16e system. This approach utilizes a custom medium access control (MAC) implementation being developed specifically to support point-to-point communications while simultaneously mapping network traffic priorities defined by Constellation Systems to those supported by the link layer. The approach also makes use of a modem being developed to support the recommendations of this study, thereby minimizing the difficulty in transitioning to a fully deployed 802.16e lunar communications system.

The lunar surface EVA suit communications system must make every effort to reduce the size, weight, and power requirements due to the limited resources available. A time-division duplex (TDD) scheme allows the uplink and downlink to be tuned to the same frequency, reducing the requirements of capabilities of the hardware in the RF front end. Consumer equipment manufacturers and service providers, as well as the standard itself, make use of the TDD option for small, power restricted devices such as smart phones and gaming devices.

Human radiation limits restrict the power output of the EVA radio to 1 Watt effective isotropic radiated power (EIRP) [6]. Therefore, the system profile will have a power limitation of 1 Watt EIRP for the EVA radio system.

S-Band has been identified as a potential frequency band that will be supported for lunar surface contingency communications [7]. The surface to Lunar Relay Satellite (LRS) link has been identified as operating in the 2.2 GHz range, using TDRSS compatible signaling and spectrum allocations.

Currently, the only profile that exists for 802.16e operations in an unlicensed band is at 5.8 GHz (upper Unlicensed National Information Infrastructure band). However, the deployments in this band are primarily fixed, point-to-point microwave systems. Other bands available for 802.16e systems are licensed bands.

In the US, early deployments of 802.16e systems will likely by in the 2.5 GHz range. However this is licensed spectrum owned by Sprint Nextel and Clearwire. It is the recommendation of this study that Constellation Systems consider the use of an 802.16e system on the lunar surface in the 2.4 GHz unlicensed band. This will promote interaction with international partners, as well as provide the possibility of a single radio platform that has the capability to communicate with the LRSs, the lunar surface wide area network, an directly in a point-to-point fashion between EVAs. In addition, ground development and testing will have the additional benefit of the extensive set of test equipment available specifically for this band.

A caveat of this approach is that terrestrial systems operating in the 2.4 GHz unlicensed band are limited to 100 mW of maximum output power. NASA would likely have to make the necessary proposals at the World Radio Conference in 2011 (WRC-2011) or obtain experimental licenses from the National Telecommunications and Information Administration (NTIA) to operate at higher powers in this band – even on the lunar surface.

Slot time, in general, should be chosen to minimize the overhead of the highest priority traffic flowing over the system. In the case of EVA, operational voice is considered a mission critical data flow (i.e. The EVA will terminate if at least voice communications between crew, or with the Lander, Habitat, or Mission Control are not maintained). For this study, it has been assumed that a G.729 codec with a 10 msec frame is utilized for voice data flows. Therefore, a slot time of 10 msec has been chosen for the 802.16e profile.

The signal bandwidth is chosen to provide the 6.829 Mbps maximum aggregate data rate requirement as identified by the design driving scenario (modified for an 802.16e PMP system), coupled with the previously identified 10 msec frame time. Additionally, it is desirable to minimize the signal bandwidth of the system for multiple reasons, not the least of which is minimizing the RF front-end noise and maximizing the possible communications range.

TABLE 5 – 802.16E AGGREGATE DATA CAPACITY (IN MBPS) FOR THE 5 MHZ SIGNAL BANDWIDTH, 10 MSEC TIME SLOT CONFIGURATION

	5 MHz, 10 msec Slot Time		
	0.25	0.5	0.75
BPSK ½	1.14	0.67	0.21
QPSK ½	2.38	1.42	0.46
QPSK ¾	3.63	2.16	0.64
16-QAM ½	4.88	2.9	0.88
16-QAM ¾	7.44	4.4	1.44
64-QAM 2/3	9.84	5.84	1.84
64-QAM ¾	11.04	6.56	2.08

Table 5 displays the aggregate data capacity (in Mbps) vs. modulation/code (left column) rate vs. uplink/downlink ratios (ratios at the top of each column). For a signal bandwidth of 5 MHz and a 10 msec slot time, the simulation results show that a data capacity of 11.04 Mbps can be achieved with a 64-QAM modulation at a 3/4's code rate.

In this study, the 802.16e system profile is being identified to support the driving design scenario in Figure 1. This scenario requires an aggregate capacity of 6.892 Mbps. However, nominal operations require an aggregate capacity of 3.414 Mbps. The aggregate capacity of the system profile chosen is 11.04 Mbps with the highest modulation/code rate pair. Therefore, the

system can support approximately 7.62 Mbps of excess capacity during nominal operations. Within this excess capacity, it is possible to transfer one HDTV data flow with the configuration shown in Table 2. However, the signal-to-noise ratio would need to be sufficiently high, with the likely possibility of requiring higher-gain antennas on the base station to specifically support these transfers. Other data flows (especially critical data flows) would operate at the lower modulation/code rate pairs in nominal operations.

A note should be made regarding the uplink/downlink ratio in the simulations performed for this study. The uplink is defined as the direction from the base station to the EVA system, whereas the downlink is the reverse link from the EVA system to the base station. The simulations were performed primarily with the concern of retrieving data from EVA mobile units in the field. This is a significant paradigm shift from Internet and 3G-type traffic, in which the majority of data is retrieved from a server residing on the Internet or the service provider networks.

However, due to the fact that 802.16e systems are reservation-based and scalable in terms of instantaneous bandwidth requirements, the maximum data capacity identified by the simulations will scale well in both capacity and asymmetry of data flows.

It was identified in our simulations that in most cases at least a 25% uplink/downlink ratio of the TDD frame was necessary to move the control signaling necessary for the 802.16e cell, however this was not fully investigated. A more efficient (potentially automated) scaling of the uplink/downlink by an 802.16e base station would better utilize the existing bandwidth.

This selection corresponds to a sampling frequency of 5.6 MHz, a Fast-Fourier Transform (FFT) size of 512 points, 8 sub-channels, a sub-carrier frequency spacing of 10.94 kHz, and a useful symbol time of 91.4 microseconds (minimal guard time) [8].

Table 6 summarizes the high level system profile parameter selections.

TABLE 6: RECOMMENDED HIGH-LEVEL 802.16E SYSTEM PROFILE

Parameter	Selection
Radio Network Topology	Point-to-Multipoint
Duplex Scheme	Time Division Duplex
Power Class	1 Watt EIRP
Radio Frequency	2.4 GHz ISM Band
Signal Bandwidth	5 MHz
Slot Time	10 msec

VIII. A NOTE ON DATA RATE VS. RANGE

Surface-to-surface communications, primarily due to the varying terrain and multipath fading mechanisms, suffer from deep fades and potential inter-symbol interference (ISI). It is not uncommon to see 10-20 dB of link margin (with free space path loss assumed) accounted for to help overcome losses due to partial blockages from terrain entering into the first Freznel zone [9].

Unfortunately, multipath fading and ISI are not phenomena that can be compensated for simply by increasing the transmit power. At this point in time, NASA does not have enough lunar site-specific information to determine what mechanisms will be needed to combat multipath effects for lunar surface missions. However, 802.16 and 802.16e systems have incorporated many mechanisms to overcome multipath fading effects, including: selectable symbol prefix extensions, diversity techniques, multiple signal bandwidth selections, variable modulation/code rate pairs, automatic repeat-request (ARQ) and hybrid ARQ schemes, etc.

This study chooses only to address the multipath fading issue indirectly, being that 802.16e has these mechanisms available. However, path loss needs to be directly considered when approximating data rate vs. range for site-specific areas.

NASA has performed a study utilizing a modified version of a very familiar terrestrial irregular terrain model [10], adapted specifically for the lunar surface. This study showed excessive path losses, exceeding at times, d^4 path loss at S-band frequencies for realistic antenna heights on the lunar surface communicating over varied terrain. Therefore, for this study a 20 dB link margin policy is enforced.

Combining this link margin policy with realistic assumptions concerning EVA and Altair antenna gains (0

dB and 2 dB, respectively), modulation/code rate pair required Eb/No values, and maximum transmit powers, data rate vs. range estimates for the identified 802.16e system are given in Table 7.

TABLE 7: DATA RATE VS. PATH LOSS AND RANGE

Aggregate Data Rate (Mbps)	Path Loss (dB)	Range (km)
11.04	-97.2	0.7
9.84	-98.9	0.9
7.44	-102.9	1.4
4.88	-107.3	2.3
3.63	-109.3	2.9
2.38	-112.6	4.2

This table represents the ideal range using a free space path loss model and a 20 dB link budget policy. However, the effects of irregular terrain will dramatically affect communication coverage at S-band frequencies.

The plot in Figure 3 is the result of a path loss analysis created with the method described in [10] for an analogue lunar site. The elevation information for this site is a modified version of Meteor Crater’s profile, appropriate for a sphere the size of the moon. The parameters of the model are set so that composition of the terrain approximated the lunar regolith composition and atmospheric effects are removed. The rings on this plot are increments of 1 km, concentric on the transmitter. The transmitter is approximately 1/3 of a kilometer northwest of the crater. The applicable range of communications, according to the data above, is likely out to the areas in yellow. However, note that the 11.04 Mbps is only achieved out to 500-700 meters from the transmitter, which is assumed to be approximately the height of Altair's antenna. Note also the shadowing effects of the crater’s rim. All communications from the lander behind the crater (to the southeast) are shadowed or blocked. This part of the study clearly illustrates the effect of the lunar surface regolith composition and its irregular terrain.

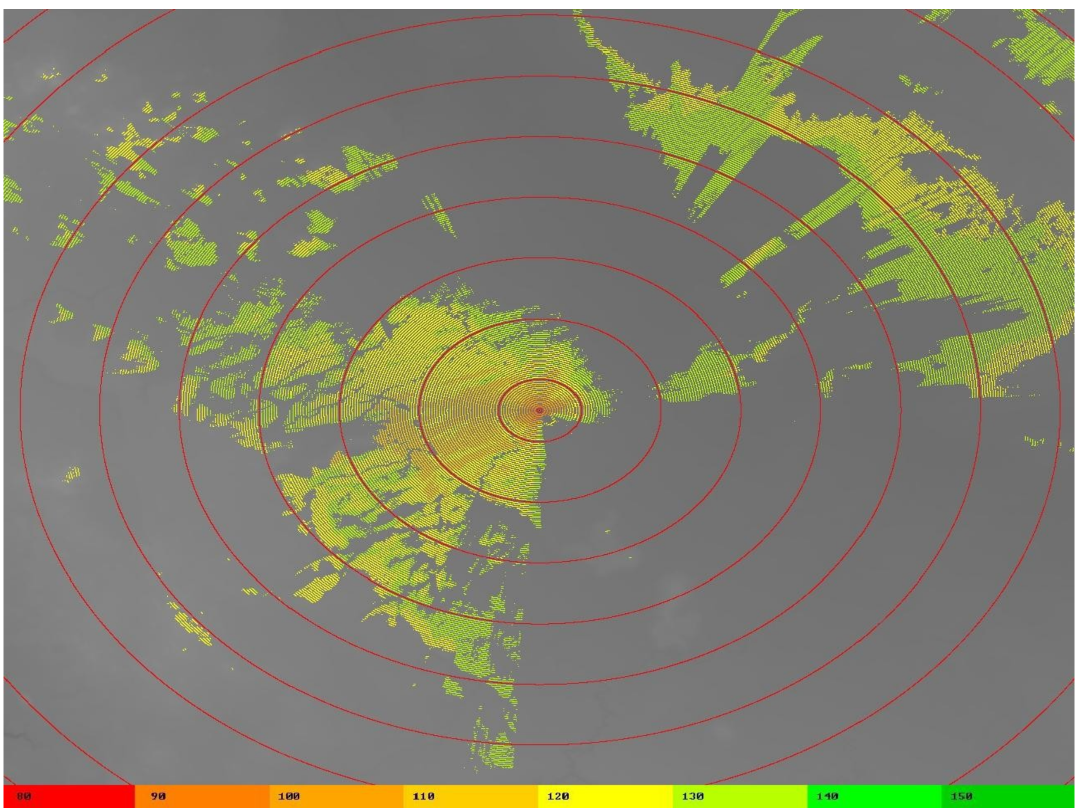

FIGURE 3 - ANALOGUE LUNAR SURFACE PATH LOSS

IX. MODEM DEVELOPMENT

Under a 2007 Phase II Small Business, Innovative Research (SBIR) contract, Toyon Corporation is developing a small form factor, software defined modem deriving requirements from the system profile presented in this report. This modem is being considered as part of a technology development effort to prototype the approaches recommended in this study. Section X through Section XII of this report describe the status of the work being done under this SBIR contract.

X. MODEM DEVELOPMENT: IEEE 802.16e WAVEFORM AND SIGNAL MODEL

The IEEE 802.16-2004 specification includes both narrowband single carrier as well as wideband waveform profiles, which employ orthogonal frequency division multiplexing (OFDM) [11]. The IEEE 802.16e Amendment expands on the original 2004 specification by incorporating scalable OFDM (SOFDM) [12]. SOFDM is targeted towards the use of mobile applications whereby a base station may need to support a wide range of mobile users. As such, the profile supports a range of channel bandwidths from 1.25 MHz to 20 MHz, all with adaptive modulation. Such scalability is designed to allow the wireless system engineer to employ hardware and software reuse in the design process.

The overall transmitter and receiver structure for the target implementation of the IEEE 802.16e waveform is shown in Figure 4. For the purposes of this paper the primary concern is with the initial acquisition of the OFDM packet as well as associated parameters, including the frequency offset. Assisting in this process, the 802.16e specification uses an innovative preamble structure. In addition to the preamble structure itself, the cyclic-prefix structure common to OFDM signals (which is also found in the IEEE 802.16 waveform) can be exploited. From Figure 4 it can be seen that the model is comparable to a classic OFDM waveform. At the receiver, a timing estimate is first performed to synchronize to the start of the OFDM packet, which has a preamble as the first OFDM symbol. This is then followed by both fractional as well as integer frequency offset estimation procedures.

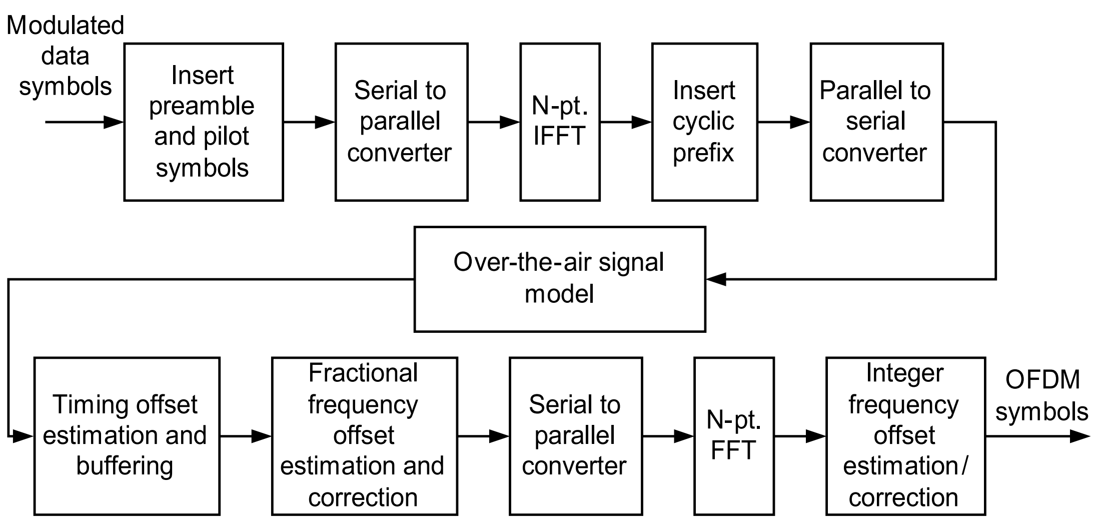

FIGURE 4 – BASIC 802.16e SIGNAL MODEL AND RECEIVER PROCESSING FOR OFDMA PROFILES

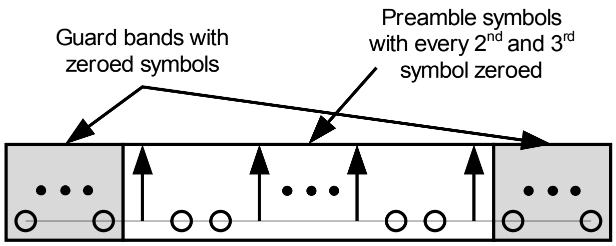

FIGURE 5 - OFDM SYMBOL STRUCTURE IN THE PREAMBLE

Figure 5 illustrates the preamble structure found in the IEEE 802.16e specification. The number of symbols in the preamble sequence is given by the equation

$$N_p = \frac{(N_{FFT} - 2N_G)}{3}.$$

where N_{FFT} is the number of points in the OFDM profile and N_G is the number of points in the guard band, which is found on both the left and right sides of the preamble sequence. This guard band length varies according to the FFT size. With 1024, 512, and 128 FFT points, the guard band lengths are 86, 42, and 10 samples, respectively. Note that the preamble sequence itself is modulated using a boosted binary phase shift keying (BPSK) encoding.

The most important feature of the preamble sequence is that only every third symbol takes on a BPSK symbol value, with all other values being equal to zero. This results in a cyclostationary structure in the time domain. In particular, the first and second half of symbols, that are output from the IFFT, are reverse conjugate pairs. As can be seen in the section on time estimation, this structure is pivotal in determining the receive signal time offset.

IEEE 802.16e signals are subject to the same channel impairments found with all wideband signals, including multipath and noise. As the primary area of discussion in this paper will be on timing and frequency offset estimation, only those channel effects that impair the estimates of those parameters are of concern. In particular, this will be carrier offset mismatch between the transmitter and receiver, as well as due to Doppler, arbitrary phase rotation, and time offset. The resulting received signal is given by

$$r[n] = e^{-j2\pi(\varepsilon n+\theta)}s[n] + v[n]$$

where $\varepsilon = {F_o}/{F_s}$ is the normalized frequency offset, θ is an arbitrary phase offset, $s[n]$ is the OFDM signal, and $v[n]$ is additive white Gaussian noise. For the frequency offset, F_s is the sampling frequency and F_o is the frequency offset due to RF carrier mismatch and Doppler. Note that in our receive signal model, and associated simulations, an oversampling rate whereby $nO = m$ with O being the oversampling rate and *n* the symbol rate is used.

XI. MODEM DEVELOPMENT: TIME AND FRACTIONAL FREQUENCY OFFSET ESTIMATION

Work presented in this paper is focused on initial acquisition of the IEEE 802.16 signal. A couple of key features of the OFDM preamble sequence are employed. The first is the fact that with only every third frequency sample of the IFFT input being populated, the resulting time sequence has a reverse conjugate output. Thus, in order to correlate with the preamble, one may simply take the first and second half and multiply the reverse sequences, which are already conjugate pairs. This procedure is shown in Figure 6.

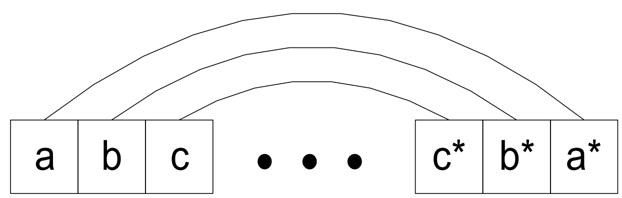

FIGURE 6 – ILLUSTRATION OF CONJUGATE SYMBOL PAIRS THAT RESULT FROM IFFT OPERATION

The second key feature of the IEEE 802.16e signal is the fact there is a cyclic prefix that is appended to the beginning of the OFDM symbol. This is nominally 1/8th of the OFDM symbol size, but can be varied in several fractional multiples. The cyclic prefix (CP) structure is shown in Figure 7 is nominally used to remove ISI in the receive waveform. Here we exploit the CP in order to have a set of symbol pairs that are separated in time, and thus prone to a common phase rotation [11].

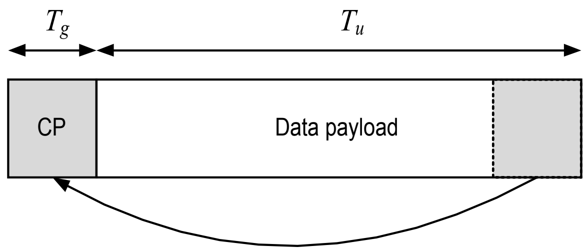

FIGURE 7 – TAIL OF DATA PAYLOAD IS INSERTED AT THE BEGINNING OF THE TIME SEQUENCE

The most important signal estimate for the entire OFDM receive chain is the time offset, which provides a start of packet estimate. The time estimate procedure focuses on finding the maximum of the equation [13]

$$T[n] = \frac{|p[n]|^2}{q^2[n]}$$

where

$$p[n] = \sum_{k=1}^{\frac{N_{FFT}}{2}} r[n+k]r[n+N_{FFT}-k]$$

and

$$q[n] = \sum_{k=1}^{\frac{N_{FFT}}{2}} |r[n+k]r[n+k]| + \sum_{k=\frac{N_{FFT}}{2}+2}^{N_{FFT}} |r[n+k]r[n+k]|$$

We note that these computations are performed at the oversampled data rate in order to obtain fine timing resolution. Alternatively, the procedure can be conducted on data at the symbol rate and a fine time resolution performed in frequency domain. However, our simulation results have not shown promising results for this procedure. Thus, while more complex in its implementation, an oversampling approach is likely to lead to more reliable performance.

Algorithm performance on simulated data is shown in Figure 8. Regions of noise as well as OFDM symbol period itself are shown in the figure. Note that while noise is sufficiently low and unlikely to lead to a false detection, several false peaks in the sequence are observed. Thus, it is likely that an absolute threshold cannot be used and therefore will require implementing a windowing search procedure in the final hardware implementation.

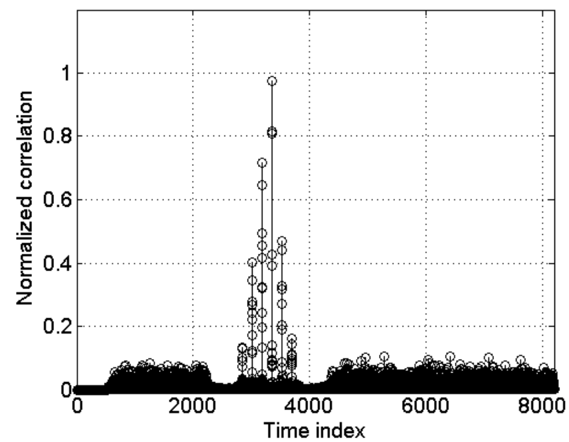

FIGURE 8 – TIME OFFSET ESTIMATION WITH SNR OF 0 DB AND N_{FFT}=128

Once a time offset, τ , has been obtained we now have knowledge of the time alignment for the first OFDM symbol, which is the preamable, along with the CP. This procedure begins by downsampling to the symbol rate.

$$z[m] = r[nO + \tau]$$

with the index of m beginning at the first time index of the CP of the OFDM symbol. We can now form the angle estimate as

$$\hat{\varepsilon} = \frac{1}{2\pi N_{CP}} \sum_{m=1}^{N_{CP}} \ln(z[N_{FFT}+m]z^*[m])$$

where N_{CP} is the length of the CP.

Simulation results for the frequency offset algorithm are shown in Figure 9. The actual frequency offset was five thousand Hertz. At each signal-to-noise ratio (SNR) one hundred Monte Carlo runs were performed. The figure shows the mean and standard deviation for the resulting frequency offset estimate. As can be seen from the figure, the algorithm achieves excellent performance and under most circumstances is able to estimate the frequency offset to within only a few tens of Hertz.

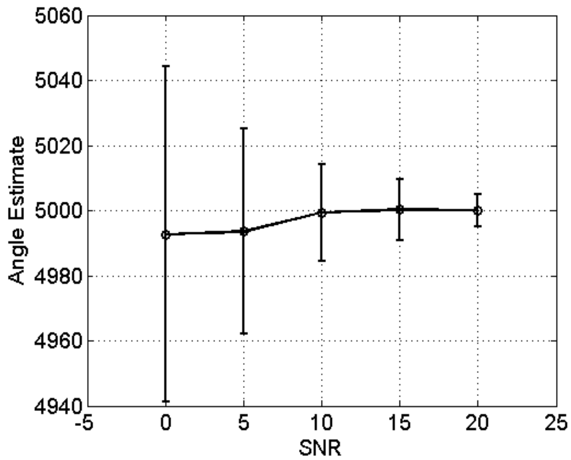

FIGURE 9 – MEAN AND STANDARD DEVIATION OF FRACTIONAL FREQUENCY OFFSET ESTIMATION WITH N_{FFT}=128

The fractional frequency offset estimation procedure is not able to estimate integer multiples of the offset to within the number of OFDM carriers times their frequency spacing. For instance, with $N_{FFT} = 128$ the maximum offset cannot be greater than about ten kHz. In the event the carrier offset is greater than this amount, an integer estimate will need to be performed in frequency after the FFT. The downside of this operation is that the preamble sequence must be known. This limits the flexibility of the hardware design as both the timing and fractional frequency offset estimates can be performed in a blind manner. The advantage of blind estimation is that instead of having to precode the preamble in the receiver design it can instead be used as a received data sequence. In this case the preamble can indicate useful features, such as the base station ID. This can of course be determined through a search procedure over the possible preamble sequences, but this is computationally intensive, and hence undesirable from the perspective of a hardware designer.

XII. MODEM DEVELOPMENT: HARDWARE ARCHITECTURE

Whereas terrestrial applications can call upon the large number of IEEE 802.16 baseband and MAC chipsets, these integrated circuits are not suitable for the harsh environment of space. In particular, without heavy shielding they are prone to failure due to the wide temperature ranges and radiation found in the lunar environment. Short of catastrophic failure, such devices are prone to disruption of normal operation due to single event upsets (SEUs). For these reasons there are many safeguards and special engineering design considerations that are used for the development of wireless transceivers to be used in space applications.

Toyon's general approach for the development of an IEEE 802.16 wireless transceiver to be used in lunar exploration is to leverage a system on a chip (SoC) design, made possible via a field programmable gate array (FPGA). We note that there are several vendors who make aerospace-grade FPGAs. For this development Xilinx solutions are of interest. Currently available Virtex-4QV parts can meet extended temperature ranges and accept over 200 krad of total ionizing dose (TID). Triple mode redundancy (TMR) can be used during the hardware design flow to mitigate SEU. We note that future aerospace-grade Virtex-5 devices will incorporate TMR-like functionality within the hardware itself, thus greatly easing the engineering effort needed to mitigate latchups and bit errors.

Thus, the EXP connector carries only digital data. One major advantage of this general design approach is that RF front-ends and FPGA base boards can be reused as appropriate. This can be important if multiple research groups would like to use the same RF front end or if the FPGA board is costly, such as when populated with an aerospace grade part.

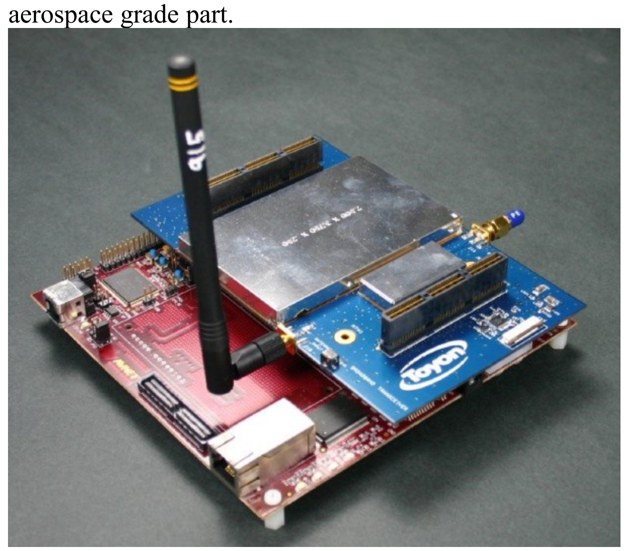

FIGURE 10 – TOYON EXP-BASED PROTOTYPE SOFTWARE DEFINED RADIO

In order to prototype wireless transceiver designs, Toyon frequently leverages EXP-based development boards and associated daughtercards [14]. Figure 10 illustrates the general concept with a prototype 500 ksps BPSK/QPSK transceiver developed on a NASA Phase I SBIR effort. The design consists of an Avnet Virtex5-LX50 based

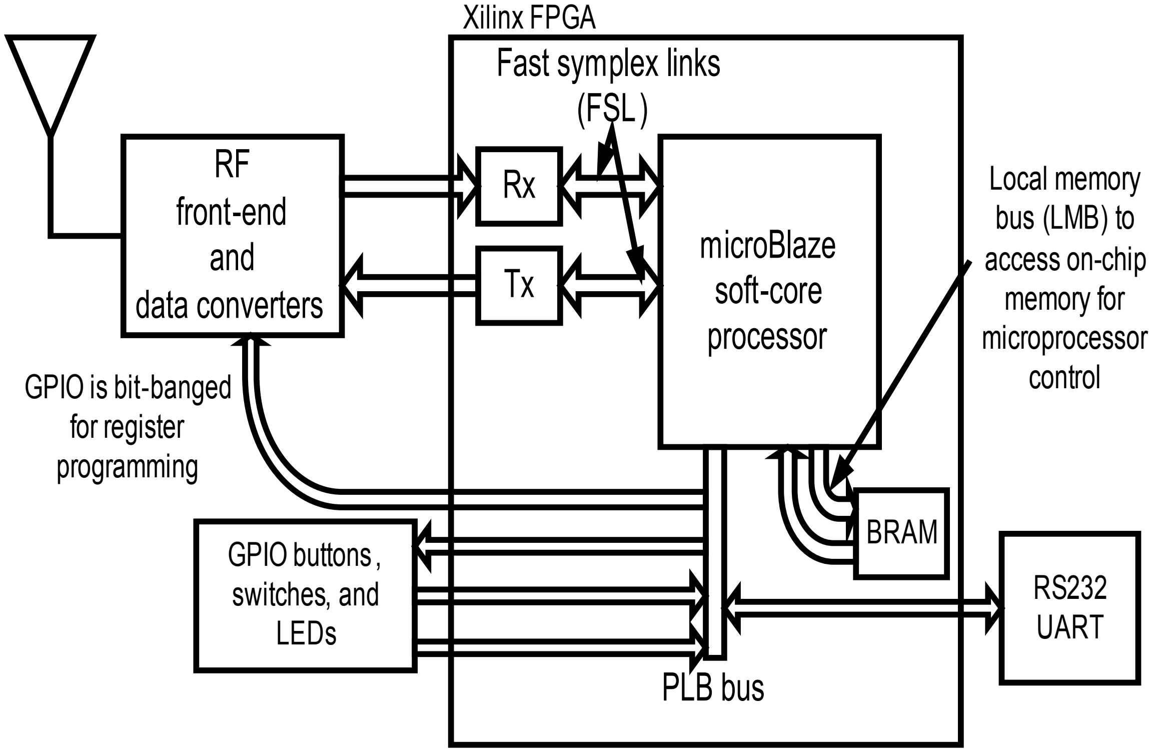

FIGURE 11 – SOFTWARE DEFINED RADIO ARCHITECTURE

prototype development board and custom Toyon-designed RF front end. The EXP RF board contains all analog processing along with associated analog and digital data converters.

The overall architecture for the prototype radio is shown in Figure 11. Here we see the SoC architecture in the form of a mixture of hardware-based baseband signal processing as well as microprocessor software control. For a typical design, all baseband processing will be performed in hardware with packet formatting and data handling performed in a microprocessor. This approach is meant to provide a compact and efficient solution that minimizes size, weight, and power. The additional benefit of the SoC approach is that additional peripherals, such as backend RS232, RS422, or Ethernet, interfaces can be incorporated within the same hardware and software design.

XIII. FORWARD WORK: TRANSITIONAL LINK LAYER

Although a high level 802.16e system profile is identified in this report that supports the data flow needs of the EVA system, it requires that a base station be the router and arbitrator of all data flows and radio resources. This presents a fundamental limitation in the application of this technology in lunar surface EVAs. This 802.16e system is capable of making very efficient use of the radio resources, support strict quality of service policies and efficient use of EVA power. However, the system would not be attractive for early sortie missions in which little or no surface infrastructure is available and the primary goal is surface exploration. At this time, this likely requires some innovation to enable point-to-point communications outside of the scope of what is offered by implementations of the 802.16e ammendment and the existing system profiles.

Therefore, alternative methods for supporting point-to-point communications are considered. Three approaches were evaluated.

The first approach is to consider options for supporting point-to-point communications within the existing standard. The mesh capability in the standard is an optional portion of for which the commercial industry has not produced viable implementations. However, the

802.16h License Exempt Working Group [15] is currently considering including such capability as an amendment to the standard. This capability does not map directly to NASA operational concepts and the draft amendments are far from being ratified. Therefore, this option will not be pursued further at this time.

The second approach consists of supporting a mutli-mode and perhaps a reconfigurable radio within the EVA suit that has the ability to communicate utilizing a hierarchy of wireless protocols. In this scheme, the EVA radio may communicate with some defined infrastructure in one mode (e.g. an 802.16e based system), and in a point-to-point fashion in another mode (e.g. in an 802.11g ad hoc mode). This approach is feasible, however there is a clear desire to minimize the amount of discrete hardware, firmware, and software components required to be implemented as part of the EVA communication subsystem. Each functional component represents a hardware/firmware/software component that requires certification for man-rated space flight, equating to higher implementation cost.

The third approach is to make use of the physical layer (antenna and RF subsystems) designed to be compatible with the 802.16e system profile identified in this report. However, a custom link layer protocol would be designed specifically for point-to-point operations and to support the data flow priorities for Constellation systems. This approach has the benefits of utilizing a common RF and antenna subsystem in both the point-to-point and infrastructure modes, directly supporting Constellation Systems priority of network traffic at the link layer and easing the transition from lunar sortie missions to missions which rely on lunar surface infrastructure. Once the lunar surface infrastructure has been built for longer duration stays, an 802.16e PMP system would ideally support local communications around lunar habitats, providing NASA systems, commercial systems, and potentially international partners a standard way of interoperating. However, even during lunar outpost missions, EVA radios must be able to transmit voice and limited suit data directly between two EVA crew members without reliance on other assets. EVA's use the buddy system where crews will always perform procedures on the lunar surface in close proximity to each other.

As part of NASA’s Exploration Technology Development Program, a development activity is underway to prototype this custom link layer and modem as part of a proof-of-concept system. The custom link layer will make use of the Toyon modem to demonstrate the approach in 2009.

The preliminary design is to use MAC frame formats already defined by the 802.16e standard. Additionally, it will only utilize the modem as an OFDM transceiver, thereby not fully utilizing the OFDMA and S-OFDMA enhancements introduced in later amendments of the original 802.16-2004 standard. This straightforward use of the modem will simplify the initial implementation, meeting EVA’s data flow requirements without excessive functionality. The demo system will make use of the pilot-inserted tones necessary for channel estimation and equalization as well as the use of controllable cyclic prefix length of the OFDM symbols, thereby alleviating some concerns related to the effects of multipath interference.

One assumption made by this implementation is that all lunar surface assets have a common timing reference. No attempt has been made as of yet to define the local clock stability or the frequency of the synchronization signal. However, the synchronization signal will be used both by the navigation subsystem as well as the communication subsystem. Prime candidates for the source of these synchronization signals (similar to the pulse per second signals obtainable from some GPS receivers) would be the Altair, Lunar Communications Tower, habitat, or even the Lunar Relay Satellites.

Utilizing this common timing reference, a scalable TDMA approach is planned. All in-network lunar nodes (e.g. EVAs, Altair, LCT, Rover, etc.) have transmit opportunities within a given amount of time, defined here as an epoch. NASA has the luxury of very well defined, scripted scenarios in which the number of in-network radio devices is defined for each mission. Therefore, combined with a common timing reference, contention periods are not necessary for network entry.

Priority of multiple-access to the radio channel in a half-duplex sense may be governed by hardware address and transmit data queued.

Figure 12 displays an example of a single epoch, in which two EVA astronauts, the Altair, and a Rover are part of the lunar surface radio network. The epoch length (time) will remained fixed, whereas the data bursts within each epoch may vary based upon the data queued for transmit within each node.

Figure 13 displays an example of a single data burst. Each OFDM symbol within a data burst will be modulated with a single code rate/error correction code combination based strictly on the priority of data carried within that symbol. Radio control information will be sent within each burst that will notify each node within the network of queued traffic and the associated priority of that data for the transmitting node. When blockages occur and radio control information cannot be shared among all radio network participants, the nodes will default to a simplified epoch/burst configuration ensuring that high priority traffic is conveyed.

The design of this transitional link layer is a work in progress and will evolve over the course of development. However, the three primary requirements associated with this development are to 1) satisfy EVA requirements, 2) keep the implementation simple, and 3) ensure an easy transition to operation within a fully-compliant 802.16e network defined by the system profile presented within this report.

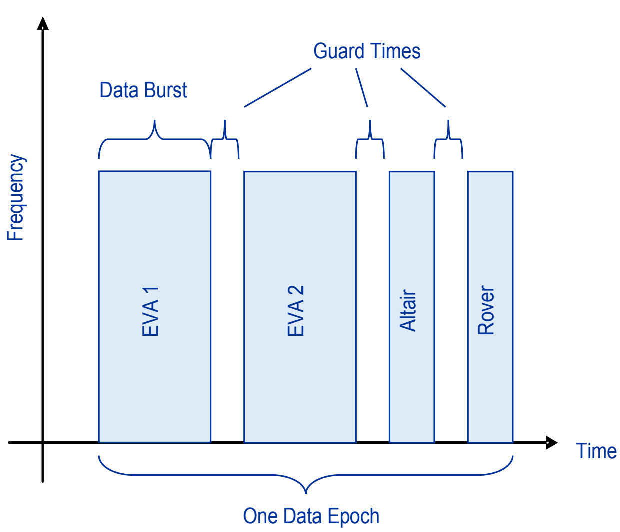

FIGURE 12 – SINGLE EPOCH OF SURFACE WIRELESS NETWORK DATA BURSTS

Similar to the modem design, this link layer logic will be prototyped on an FPGA utilizing a soft microprocessor core for algorithm execution as well as data formatting. Later versions of the prototype will aim to integrate all baseband and protocol processing on a single FPGA, with the goal of targeting a radiation tolerant implementation.

XIV. CONCLUSIONS

This study has identified a high level system profile of an 802.16e deployment (defined by the parameters in Table 6) that meets the data flow requirements of the EVA system. However, this 802.16e system is an infrastructure based system similar in operation to cellular phone networks.

Lacking immediate infrastructure on the lunar surface, a network in which all radio resources are arbitrated by a central controller is not a viable solution. Therefore, an intermediate approach is to design a radio that has a migration path to interoperate with an 802.16e based radio network, yet meet immediate requirements for initial sortie missions.

This study also introduces a current work in progress, which couples the modem development of the Toyon Corporation (under a 2007 Phase II Small Business, Innovative Research contract), with a custom link layer that includes a primary goal of easing the transition to an infrastructure-based system.

Design, development, and integration of the first prototype radio system will extend through September of 2009.

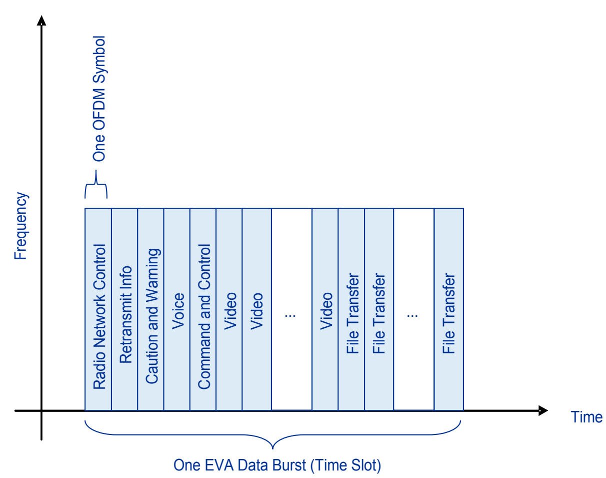

FIGURE 13 – SINGLE EVA DATA BURST

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